Evidence of the SM Higgs Boson in CMS in the Decay Channel into Tau Leptons

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Higgs Hunting Workshop
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for the CMS collaboration

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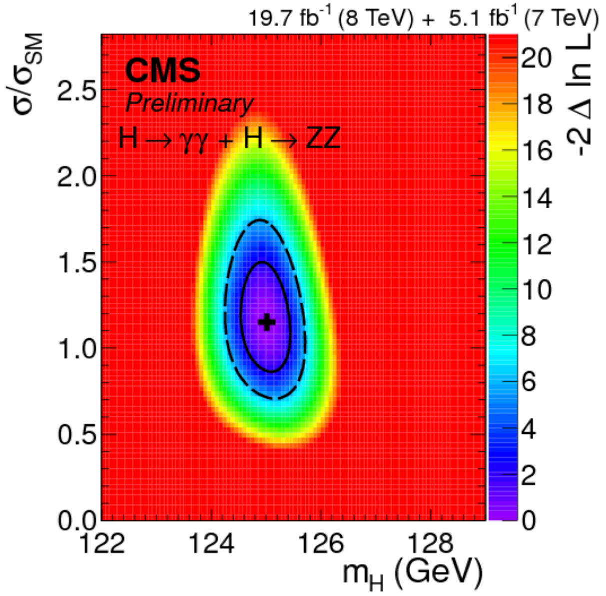
Motivation

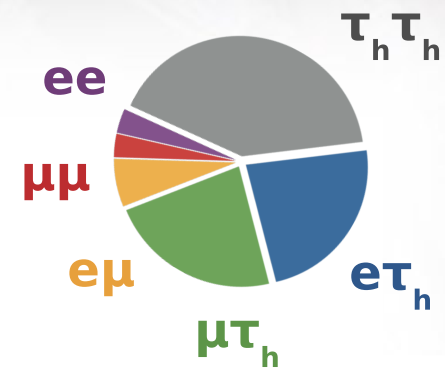
- A **Higgs boson has been found** at a mass of ~125 GeV
  - Signals have been seen in
    $H \to \gamma\gamma$ (5.6σ),
    $H \to ZZ$ (6.5σ),
    $H \to WW$ (4.7σ)
- Coupling to **Fermions**?
  - Fundamentally different than coupling to bosons
  - Only indirect evidence from bosonic channels
  - **Down-type** fermion couplings can be probed with $H \to \tau\tau$



CMS-PAS-HIG-14-009

Overview

- High **backgrounds**, dominated by:



Z → ττ:

Normalized to measured cross section, **Shape** from embedded data events

Z → ee/μμ:

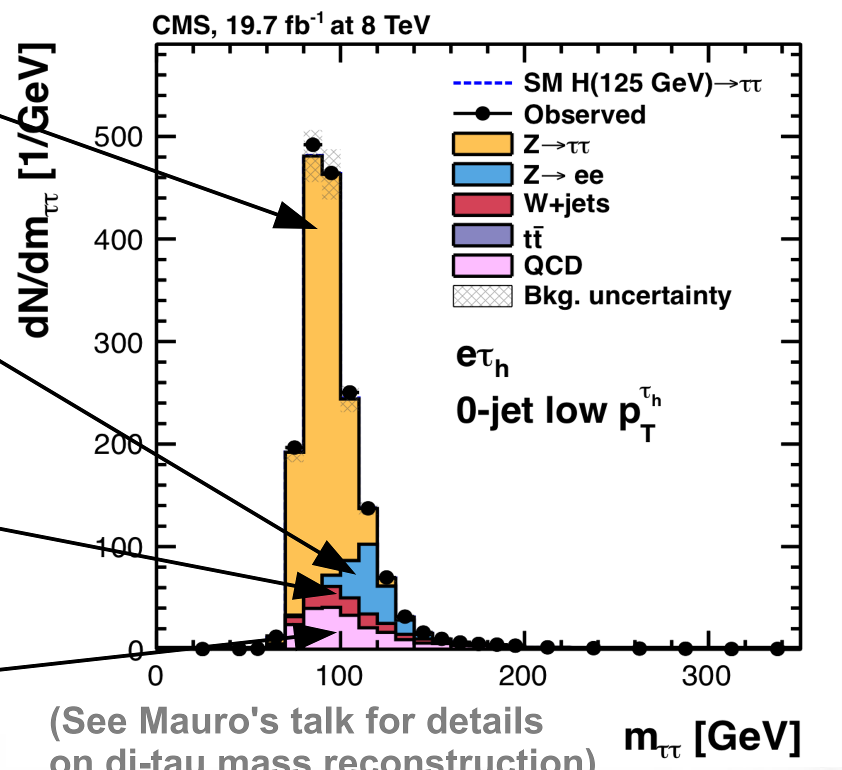
Shape and **Normalization** from fit to data in 0-jet category

W + Jets:

Normalized to data in high m_T sideband, **Shape** from Simulation

QCD Multijet:

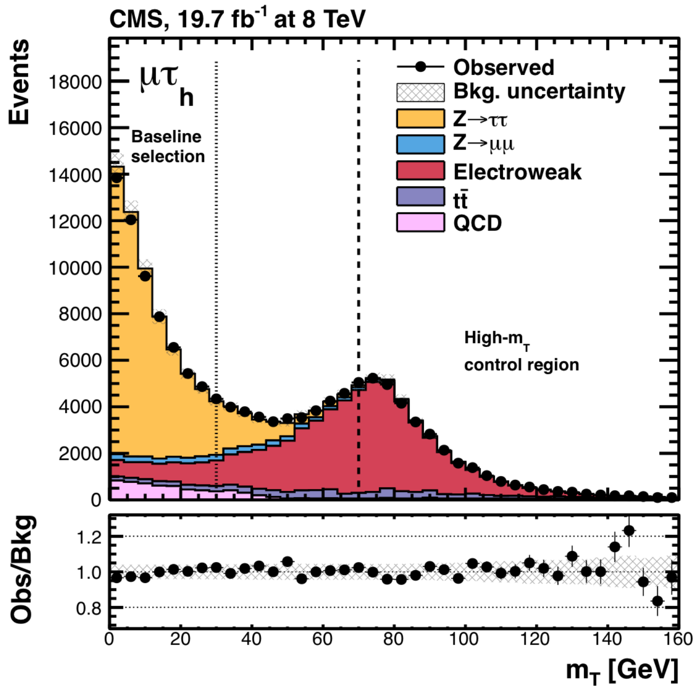
Shape and **Normalization** from Same Sign data



(See Mauro's talk for details on di-tau mass reconstruction)

Background Estimation

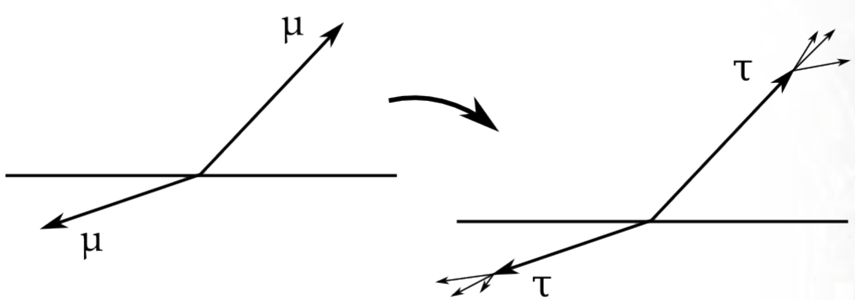
W + Jets:

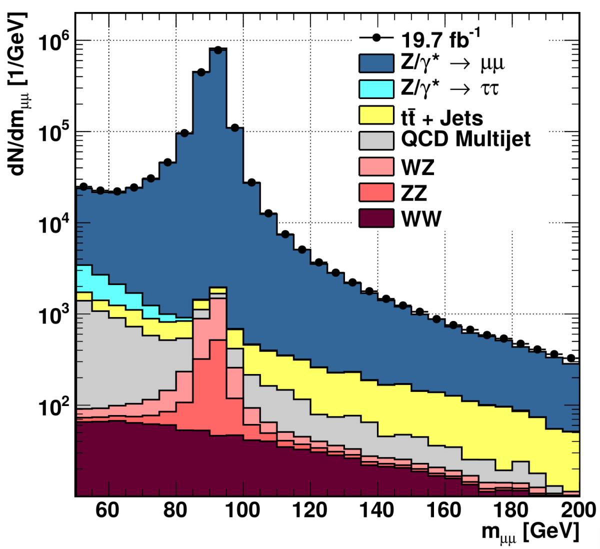


$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi)}$$

pure W + Jets sideband

Z → ττ:





very pure di-muon selection

IEKP-KA/2014-09

Event Categorization

VBF: | **1 Jet:** | **0 Jets:**

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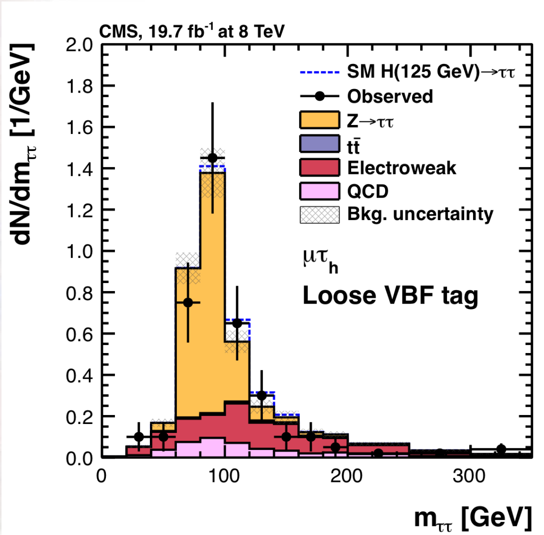
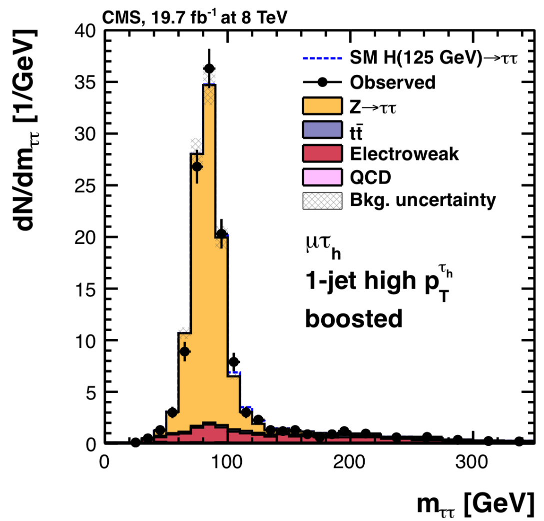
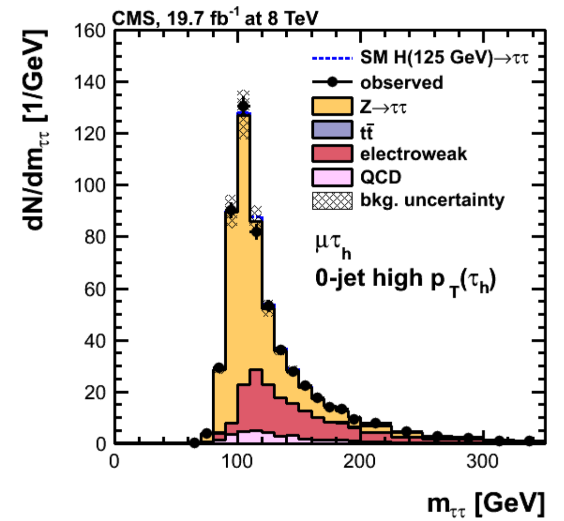


- Low event statistics
- High S/B



- Exploit boost of the Higgs system: Improved mass resolution

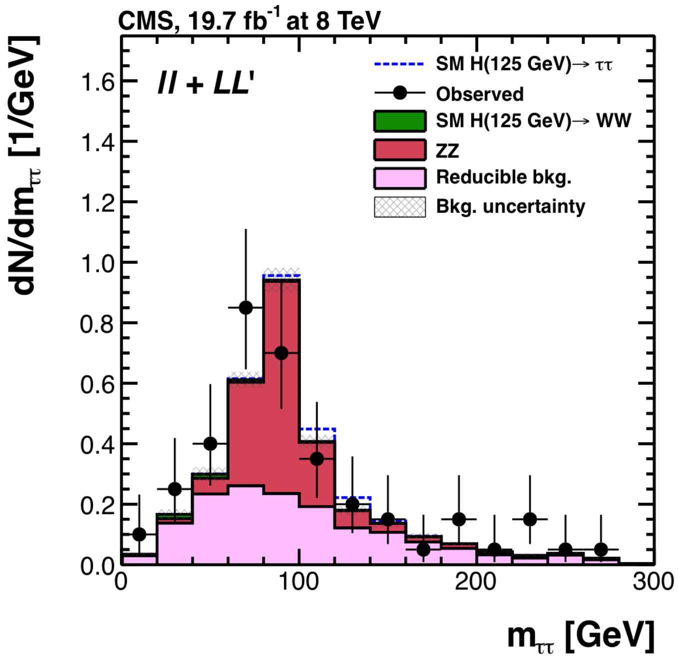


- Low S/B
- Important for Constraining Nuisance Parameters

$\mu\tau_h$ channel

VH Associated Production

- More than 2 leptons in the event
- Easy to **trigger**
- Low SM Background
- But: Low cross section
- WZ/ZZ is **irreducible background**
  - From **simulation**
- Other background have **misidentified leptons**
  - estimated from **data**



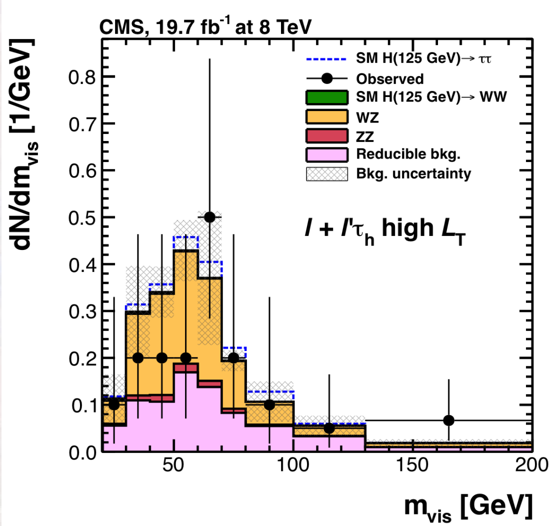
Channels analyzed:

$Z(ee, \mu\mu)H(\mu\tau_h, e\tau_h, \tau_h\tau_h, e\mu)$

$W(e\nu, \mu\nu)H(\mu\tau_h, e\tau_h, \tau_h\tau_h)$

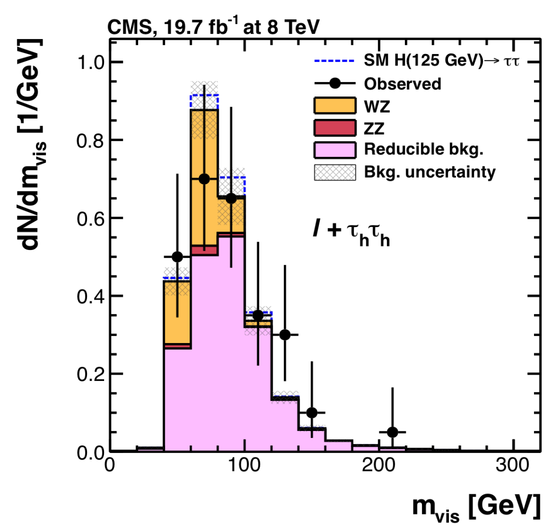
VH Categorization

WH semi-leptonic:



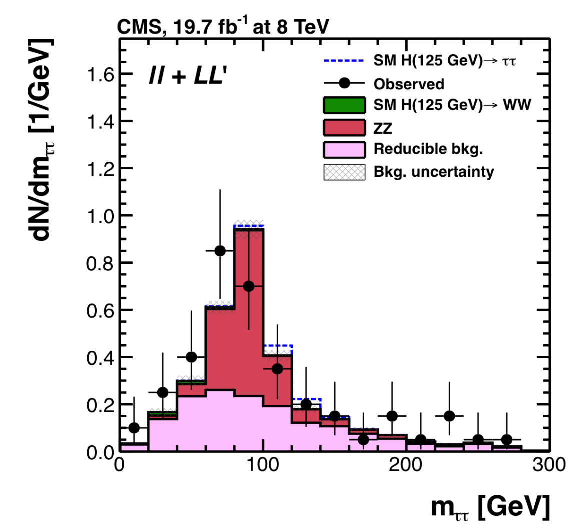
- 3 Leptons
- Dominated by WZ pair production

WH hadronic:



- 3 Leptons
- Dominated by mis-identified jets

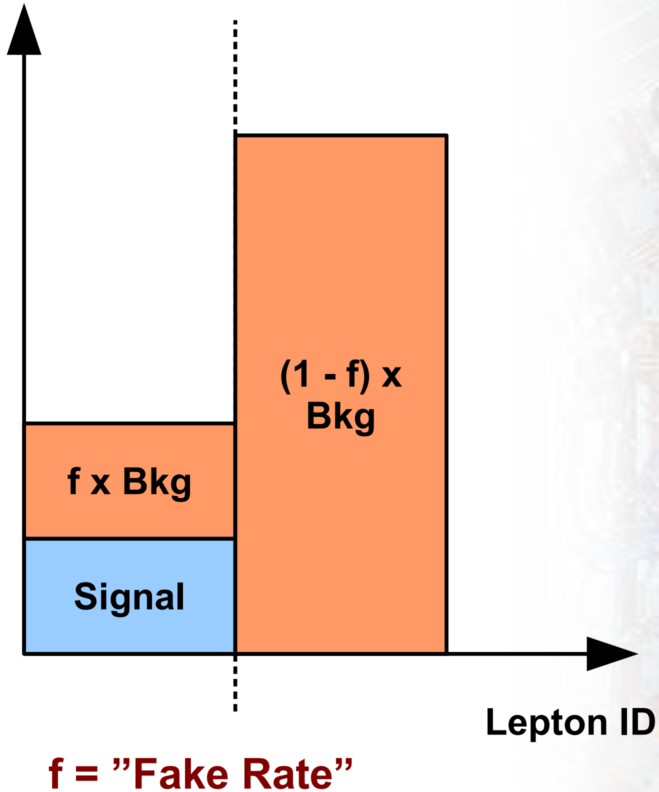
ZH:



- 4 Leptons

VH Background Estimation

- Major background from **misidentified leptons**
- Select background-enriched region by **inverting lepton ID** or isolation
- Weighting with ”Fake Rate” gives estimation in signal region
- Works also in 2D for backgrounds with different misidentified leptons
  - e.g. e+μ in $e\mu\tau_h$ channel



Fake Rate Measurements

- Fake Rate measured in well-known **control regions**
  - For example, $Z \rightarrow \mu\mu$ events
- Fake Rate depends on **many parameters**
  - p_T and η of the lepton
  - Jet multiplicity
  - Hard physics process
- Major source of **systematic uncertainty**
  - 20-30% in most channels

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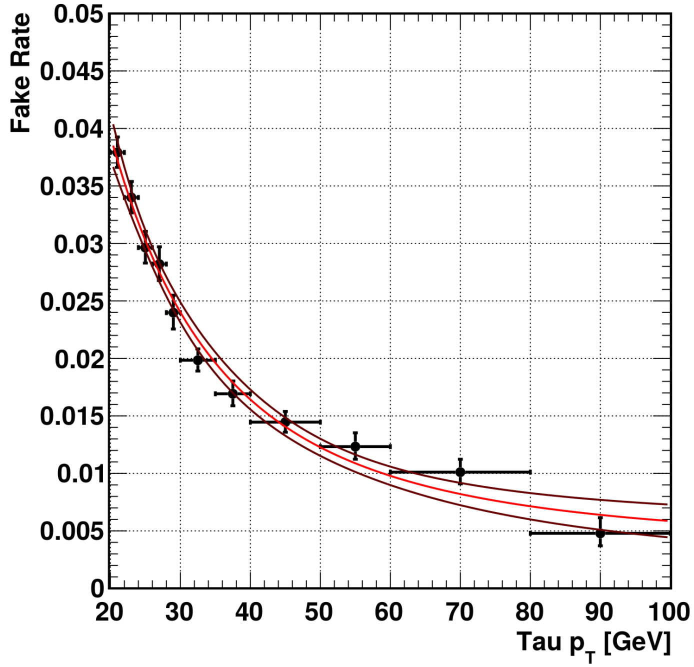
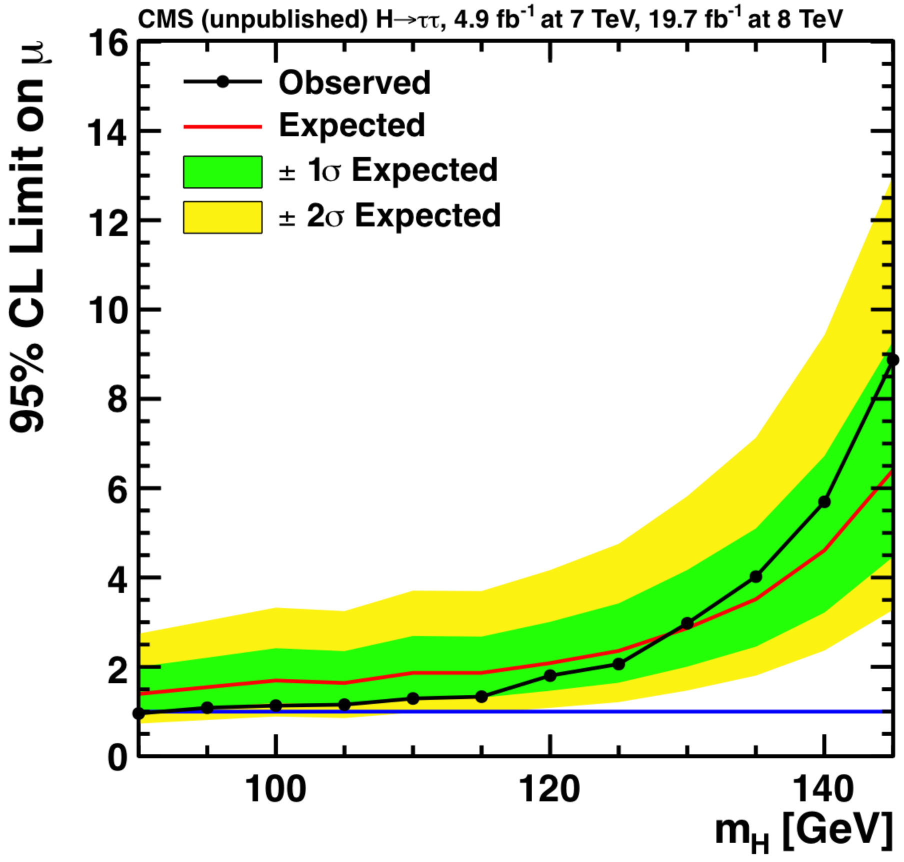
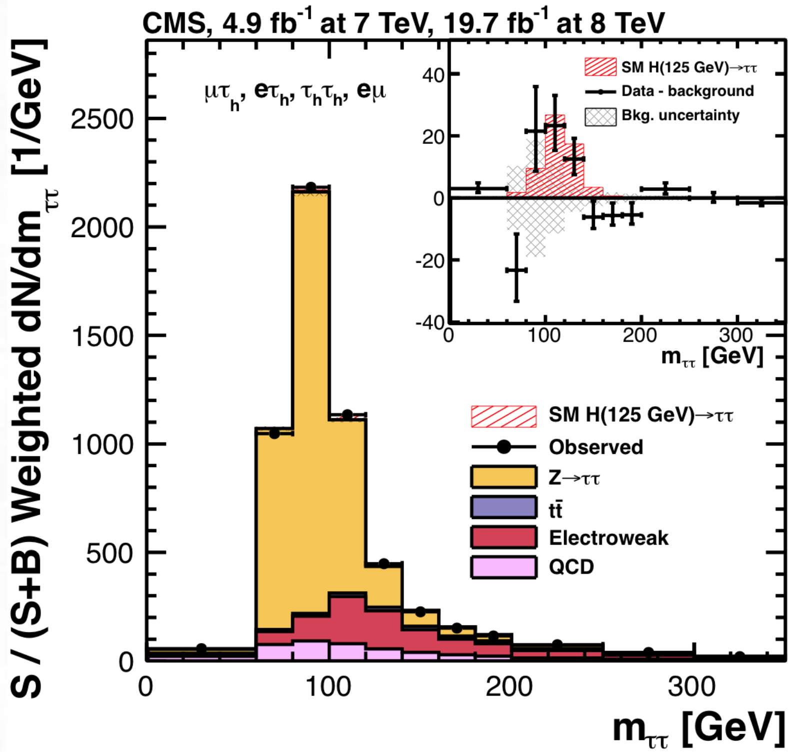


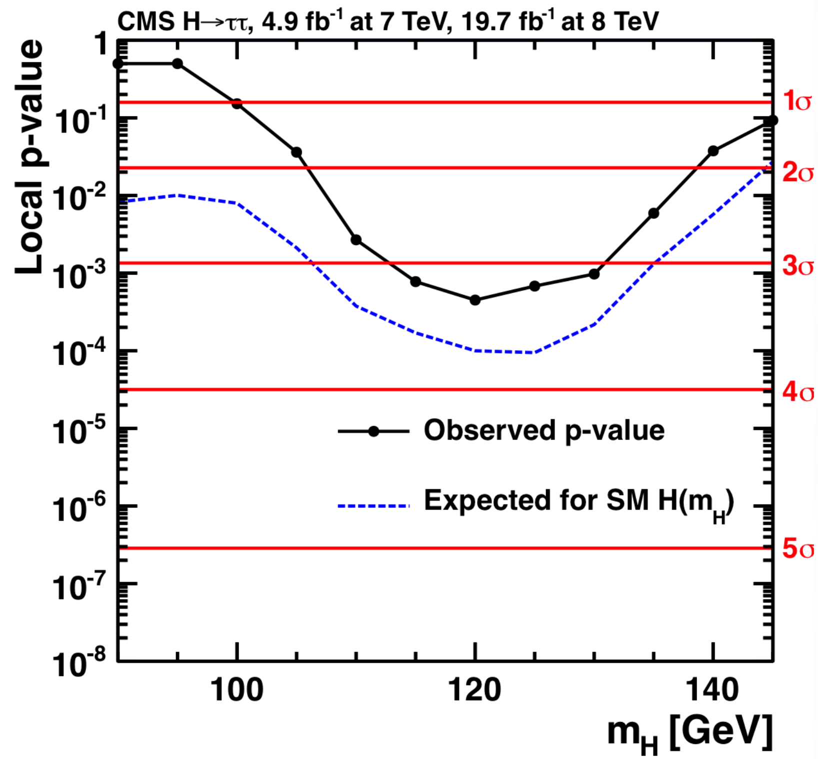
VH Result



- No signal observed in VH channels
- Sensitivity dominated by **statistical precision**
- High sensitivity at **low mass**

Full Combination

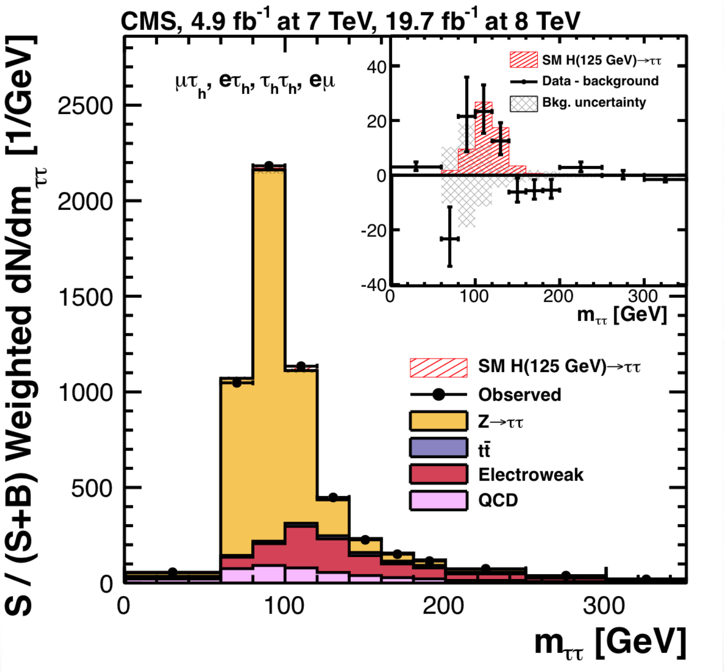




- Signal builds up slowly in various **channels and categories**
  - Visualized in **S/(S+B) weighted** mass distribution
- CMS sees **3.2σ** evidence for the H → ττ decay

Conclusions

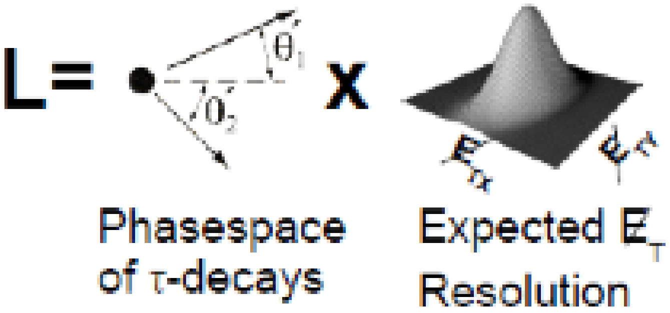
- **SM Higgs Results** in the ττ channel have been presented
  - Analysis is complex due to high backgrounds and the **combination of many channels** and categories
  - Different analysis strategy in VH channels
- CMS sees an **excess around 125 GeV** at **3.2σ** significance!
- Evidence for coupling of Higgs boson to **tau leptons**!
- More on H → ττ and other fermionic channels in **Mauro's talk**



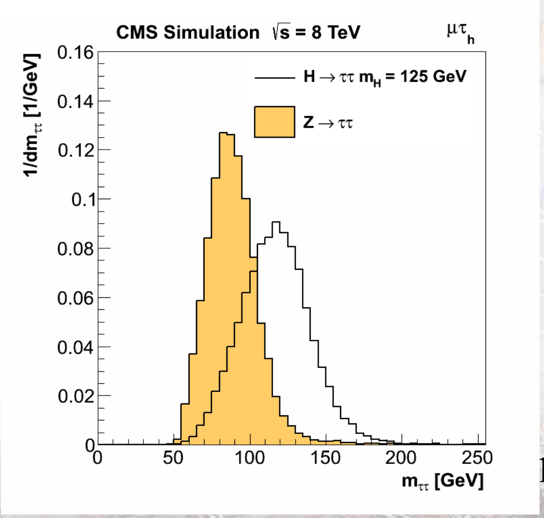
Backup

Di-tau mass reconstruction

- Use di-tau mass as **discriminating variable**
- Undetected neutrinos lead to **underestimation** of the di-τ mass
- Likelihood-based method to find mass which is **most compatible** with:
  - Tau decay kinematics
  - Visible decay products
  - E_T^{miss} + uncertainty

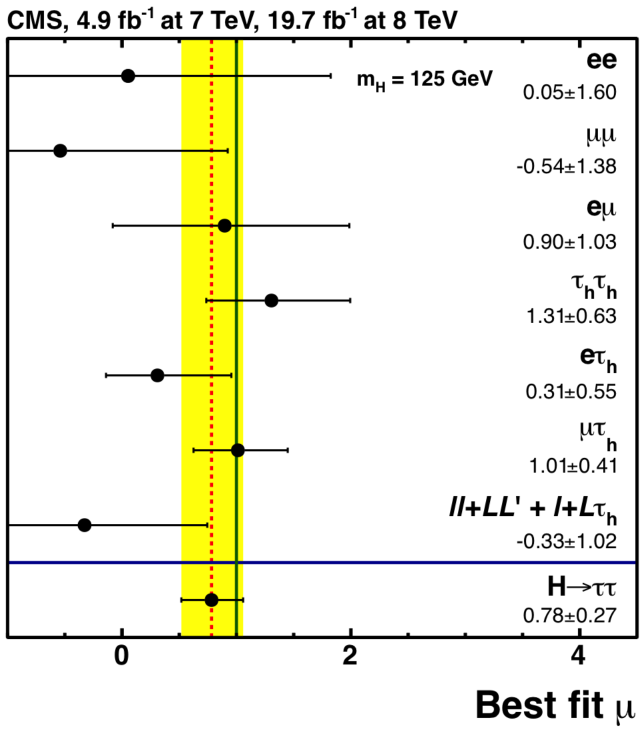


- Mass resolution:
  - 10% to 20% (depending on final state)

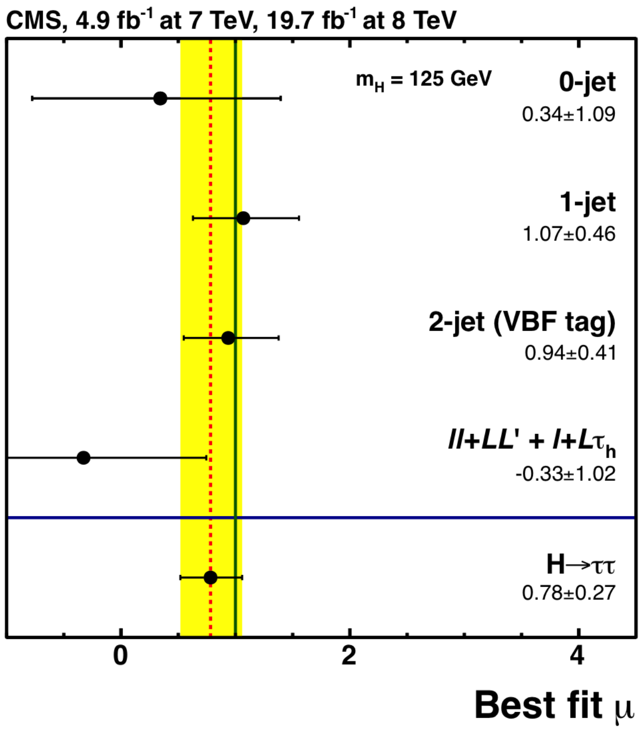


Best Fit Signal Strength

By channel:



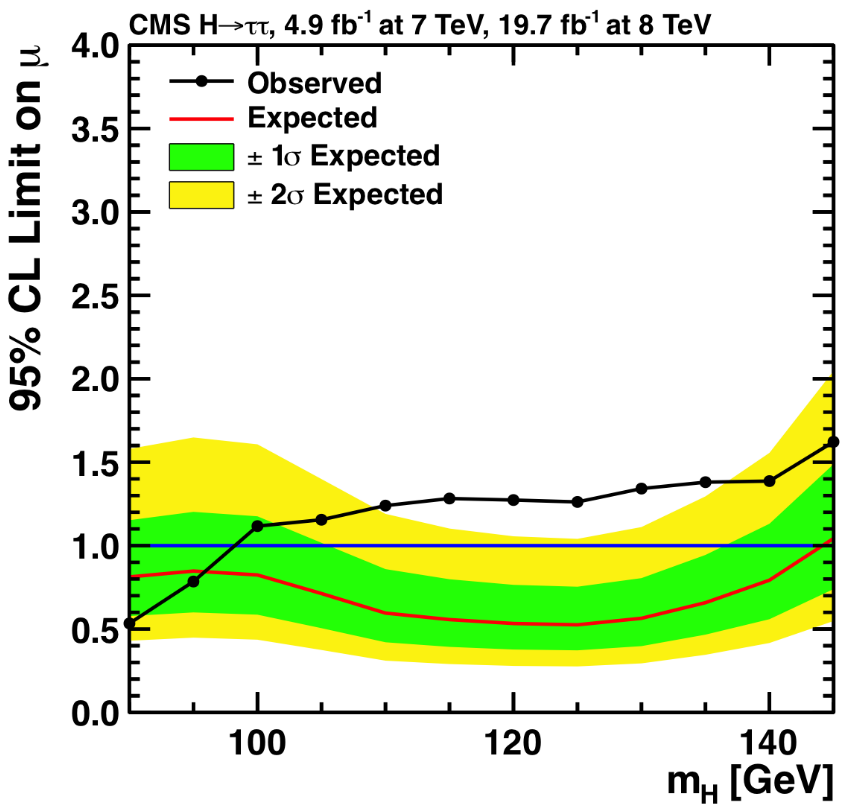
By category:



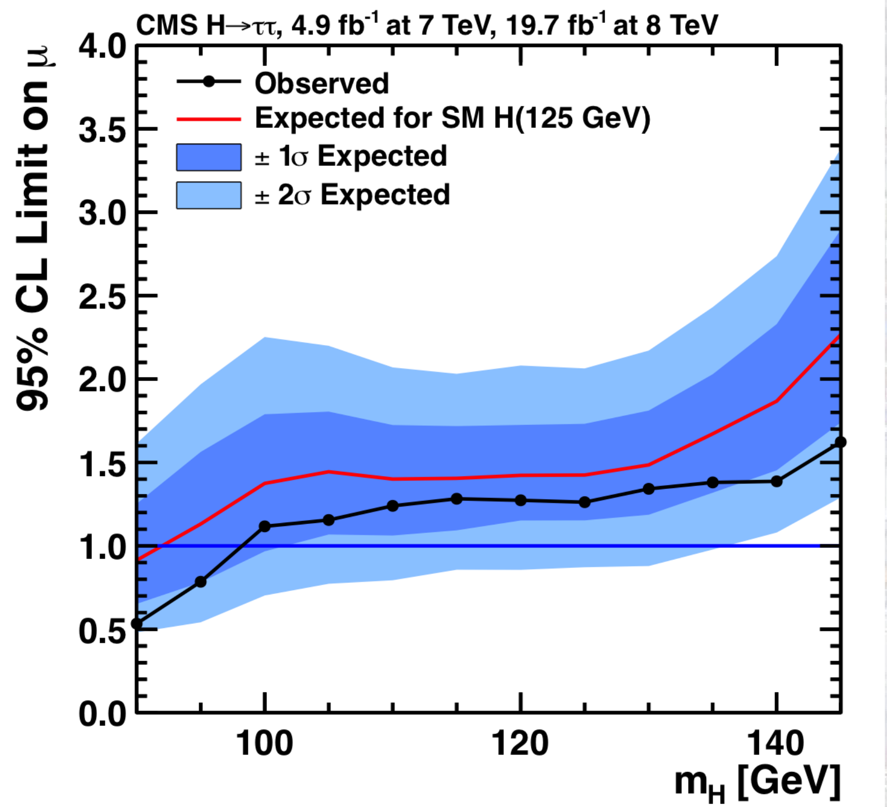
- Important nuisance parameters **shared** between channels and categories (**constrained** by high statistics categories in global fit)
- Best fit **μ = 0.79 ± 0.27**

Expected Exclusion Limits

Background only:

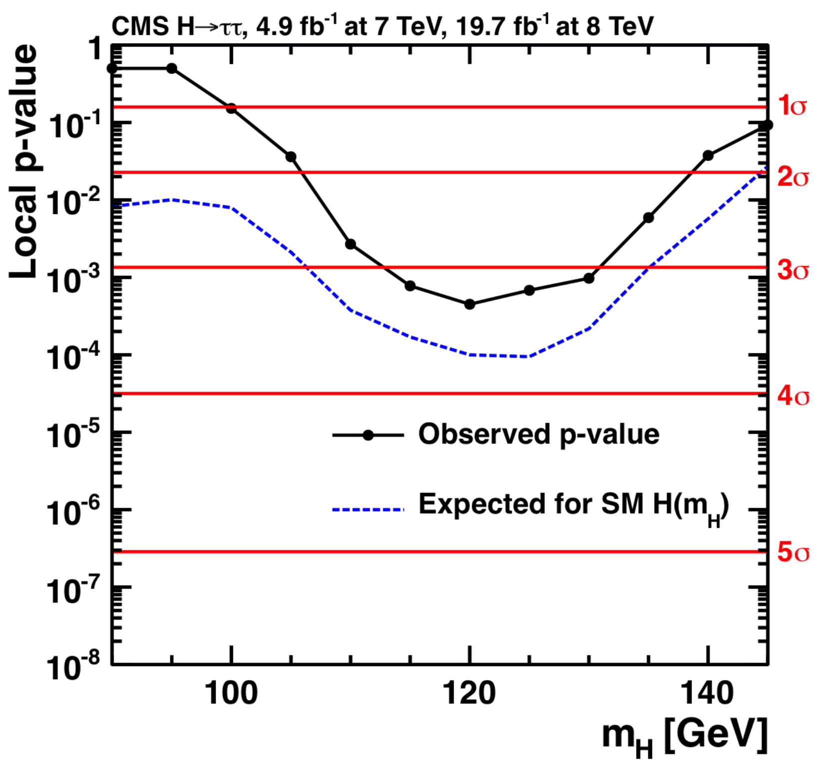


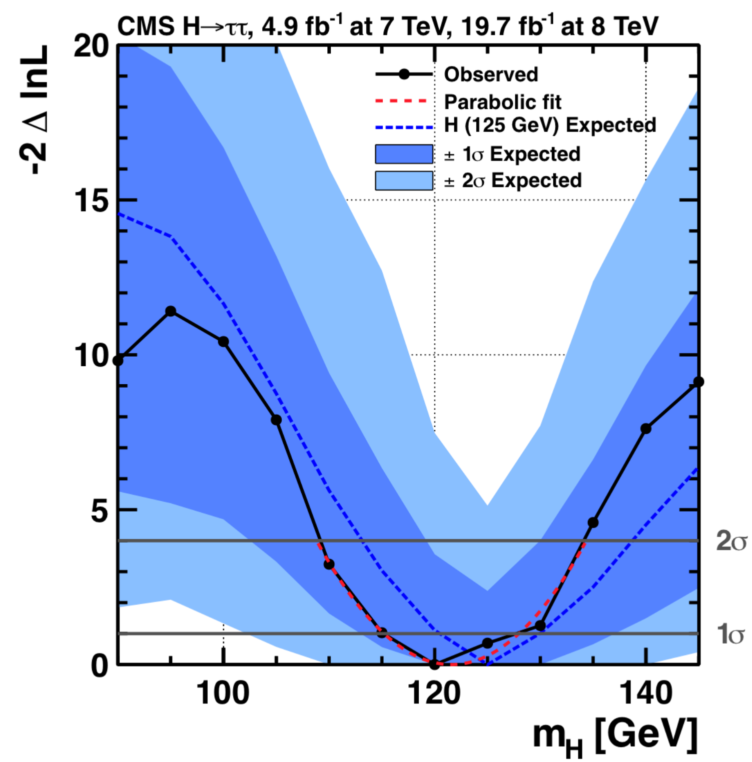
1x SM + Background:



- Excess is **compatible with SM Higgs** boson hypothesis over wide mass range

p-value and Mass Scan

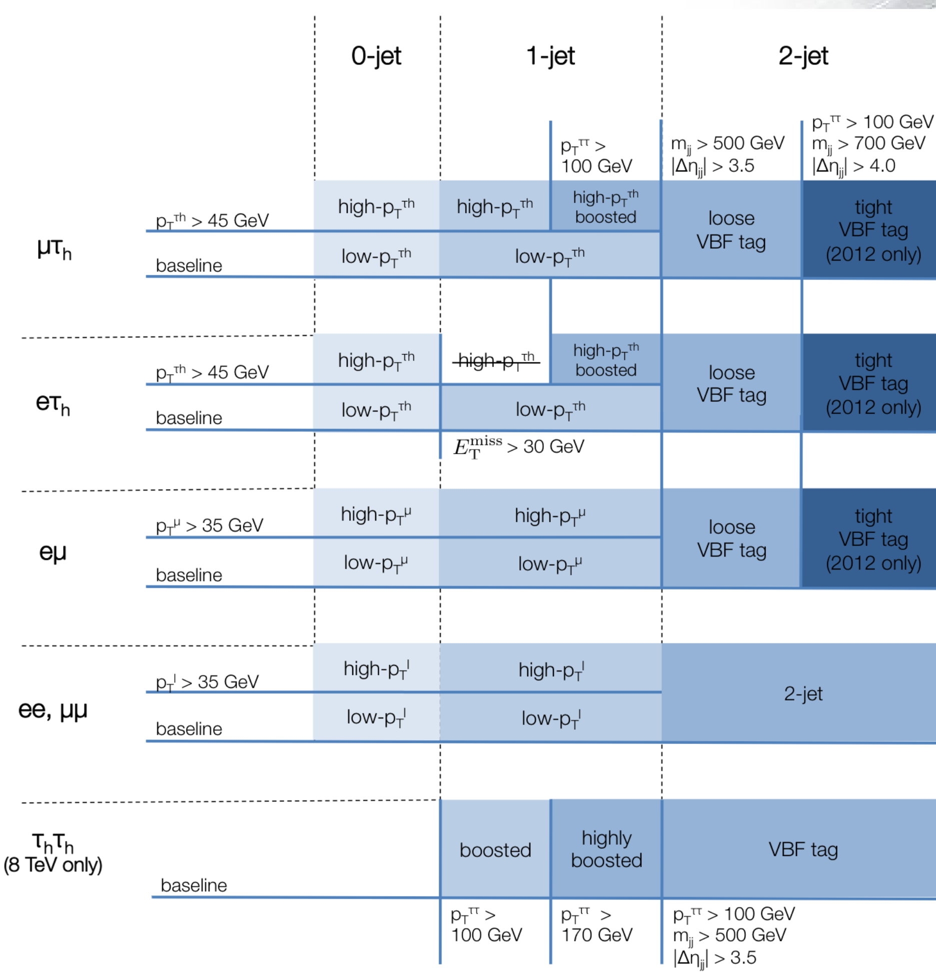




- Largest **observed significance** (3.3σ) at m_H = 120 GeV
- **Mass scan**: **m_H = 122 ± 7 GeV**

Event Categorization

- Use full event kinematics to **categorize events**, based on
  - jet multiplicity
  - $p_T^{\tau\tau} = |\vec{p}_T(L) + \vec{p}_T(L') + E_T^{miss}|$
  - $p_T(\tau_h / \tau_l)$
- Optimizes **overall sensitivity**
- Less categories in the 7 TeV data
- **58 categories** in total
  - Fit for signal in all of them



Categories in 8 TeV

Event Categorization at 7 TeV

Channel	Selection	0-jet	1-jet		2-jet
				$p_T^{\tau\tau} > 100$ GeV	$m_{jj} > 500$ GeV, $\lvert\Delta\eta_{jj}\rvert > 3.5$
$\mu\tau_h$	$p_T(\tau_h) > 45$ GeV	high $p_T(\tau_h)$	high $p_T(\tau_h)$	high $p_T(\tau_h)$ boost	VBF tag
	baseline	low $p_T(\tau_h)$	low $p_T(\tau_h)$		
$e\tau_h$	$p_T(\tau_h) > 45$ GeV	high $p_T(\tau_h)$	high $p_T(\tau_h)$		VBF tag
	baseline	low $p_T(\tau_h)$	low $p_T(\tau_h)$		
			$E_T^{miss} > 30$ GeV		
$e\mu$	$p_T(\mu) > 35$ GeV	high $p_T(\mu)$	high $p_T(\mu)$		VBF tag
	baseline	low $p_T(\mu)$	low $p_T(\mu)$		
ee, $\mu\mu$	$p_T(l) > 35$ GeV	high $p_T(l)$	high $p_T(l)$		2-jet
	baseline	low $p_T(l)$	low $p_T(l)$		

Analysis Strategy

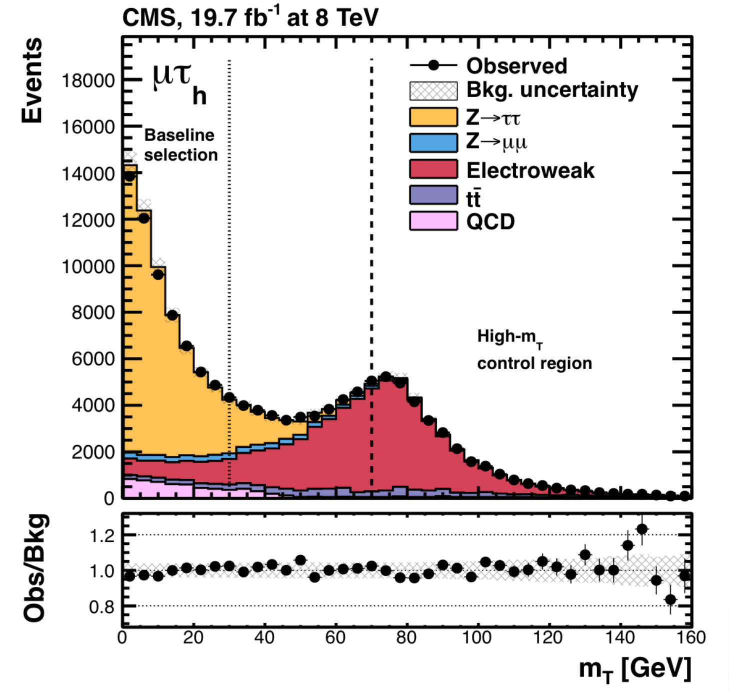
- Goal: Measure **coupling** of $H \rightarrow \tau\tau$ ($H \rightarrow WW$ is background)
- Final states with **2 leptons**: e, μ or τ_h (More than two leptons in VH)
- Light leptons from tau decays are **soft**
  - Need **low p_T thresholds** (→ cross triggers)

Channel	Offline p_T Threshold
$\mu\tau_h$	$p_T(\mu) > 20$ GeV, $p_T(\tau_h) > 30$ GeV
$e\tau_h$	$p_T(e) > 24$ GeV, $p_T(\tau_h) > 30$ GeV
$\tau_h\tau_h$	$p_T(\tau_h) > 45$ GeV
ee, eμ, μμ	$p_T(l_1) > 20$ GeV, $p_T(l_2) > 10$ GeV

- Isolated leptons to suppress e.g. QCD multijet events with jets misidentified as leptons
- $M_T(l, E_T^{miss}) < 30$ GeV to suppress W+Jets events

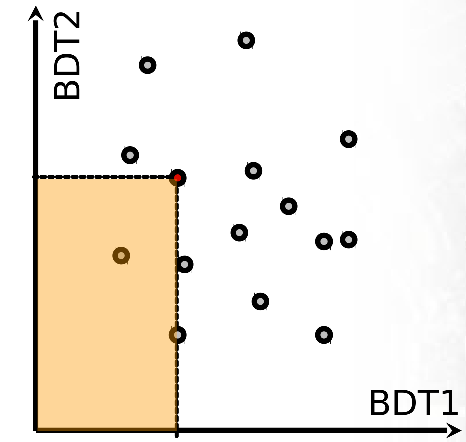
Background Rejection

- Very channel specific in general
  - Differentiate between
    - Irreducible backgrounds (same final state)
    - Reducible backgrounds (one or more objects misidentified)
- Main backgrounds:
  - $Z \to \tau\tau$
  - $Z \to ee/\mu\mu$
  - W + Jets
  - QCD Multijet
  - $t\bar{t}$

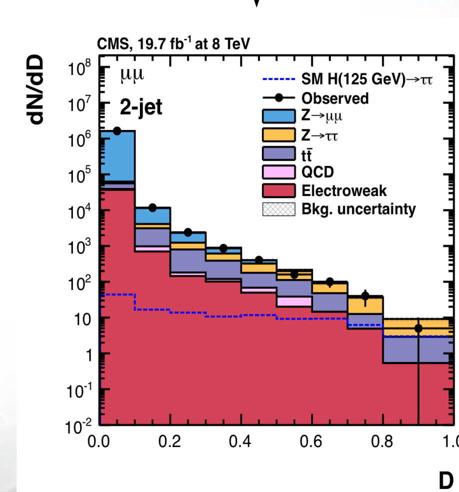


Same Flavor Dilepton Channels

- Different analysis strategy
- No τ_h reconstruction needed
- Additional **direct Z → ll** background
- Train **two BDTs**
  - BDT1: Separate Z → ll from Z/H → ττ
  - BDT2: Separate Z → ττ from H → ττ

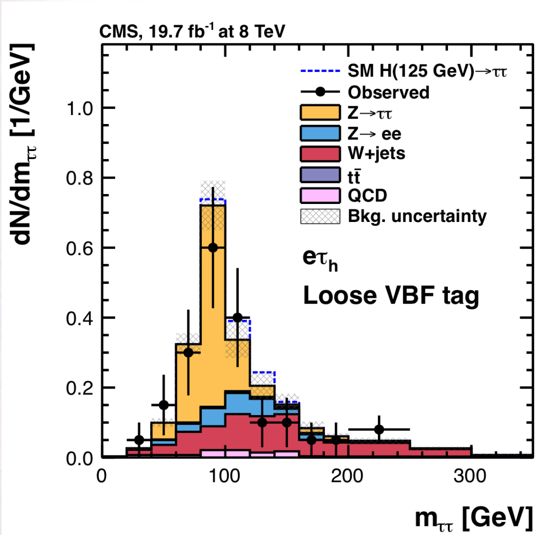


$$D_{\mathrm{cat}} = \int_0^{\mathrm{BDT}_1} \int_0^{\mathrm{BDT}_2} f_{\mathrm{cat}}^{\mathrm{sig}}(\mathrm{BDT}'_1, \mathrm{BDT}'_2)\, \mathrm{dBDT}'_1\, \mathrm{dBDT}'_2$$



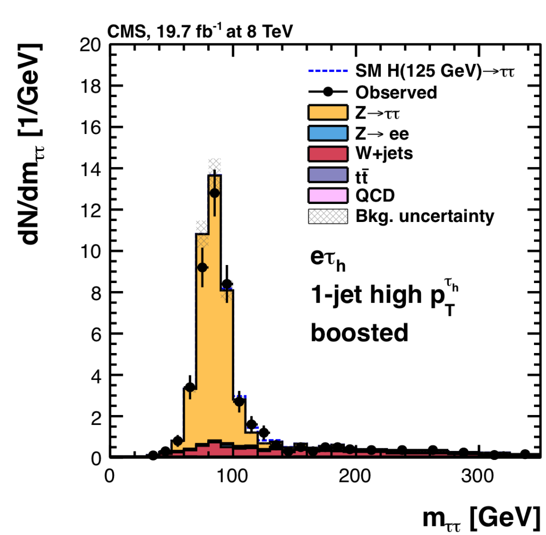
Di-Tau Mass Distributions ($e\tau_h$)

VBF:



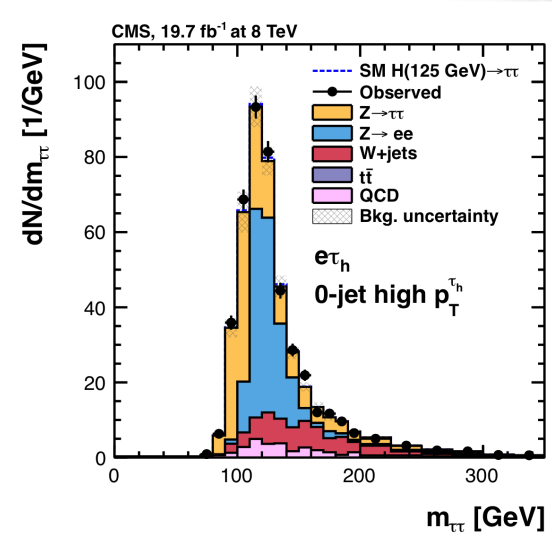
- Low event statistics
- High S/B

1 Jet:



- Exploit boost of the Higgs system: Improved mass resolution

0 Jets:

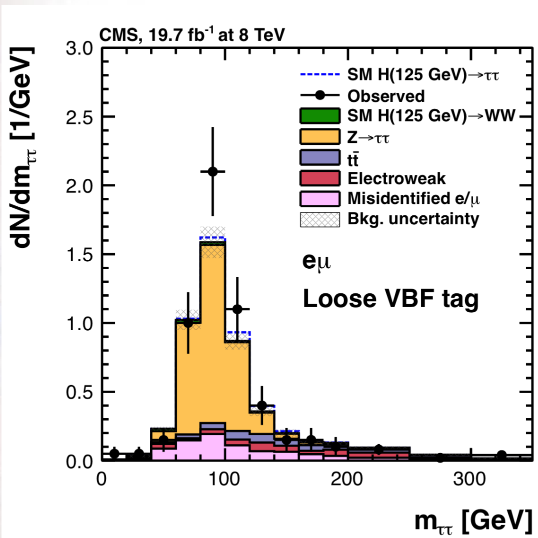


- Low S/B
- Important for Constraining Nuisance Parameters

$e\tau_h$ channel

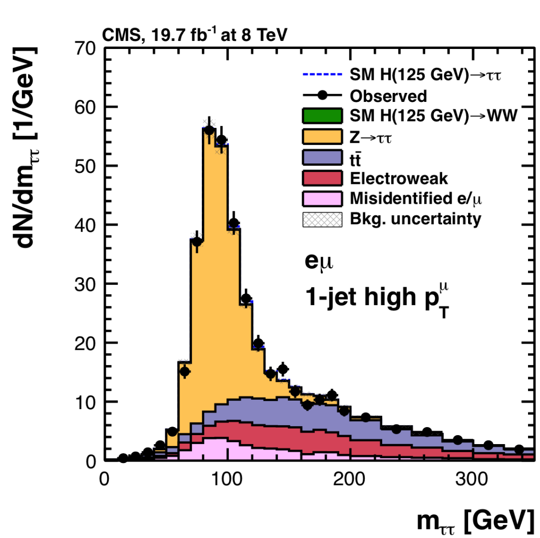
Di-Tau Mass Distributions (eμ)

VBF:



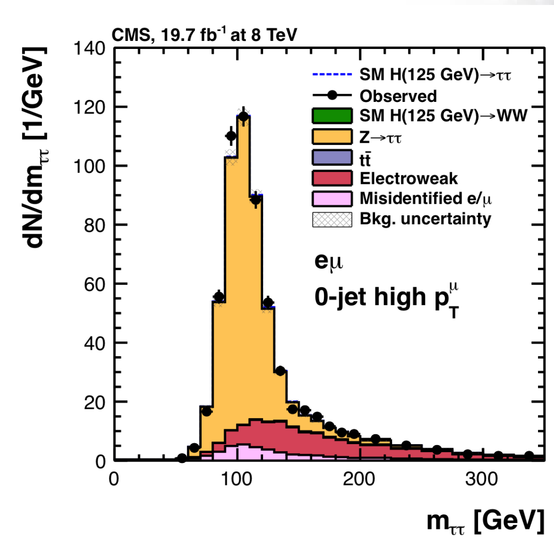
- Low event statistics
- High S/B

1 Jet:



- Exploit boost of the Higgs system: Improved mass resolution

0 Jets:

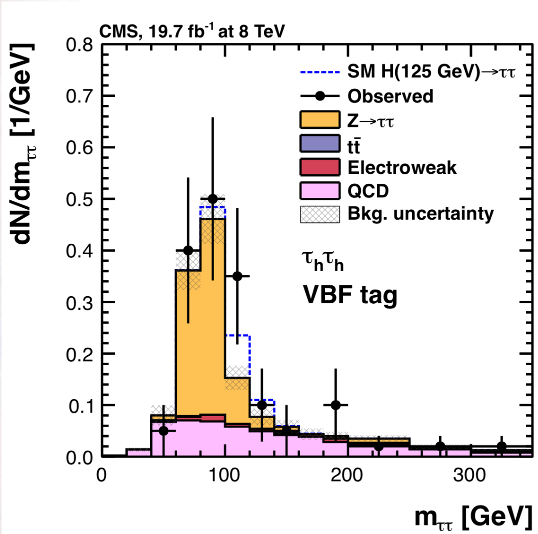


- Low S/B
- Important for Constraining Nuisance Parameters

eμ channel

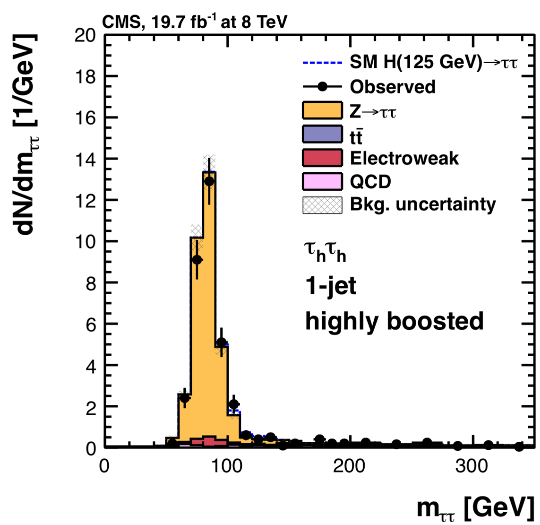
Di-Tau Mass Distributions ($\tau_h \tau_h$)

VBF:



- Low event statistics
- High S/B

1 Jet:



- Exploit boost of the Higgs system: Improved mass resolution

0 Jets:

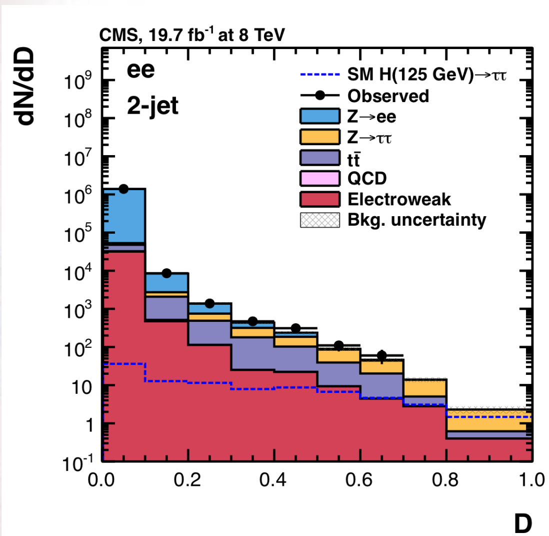
No 0-Jet category due to trigger requirements in this channel

- ~~Low S/B~~
- ~~Important for Constraining Nuisance Parameters~~

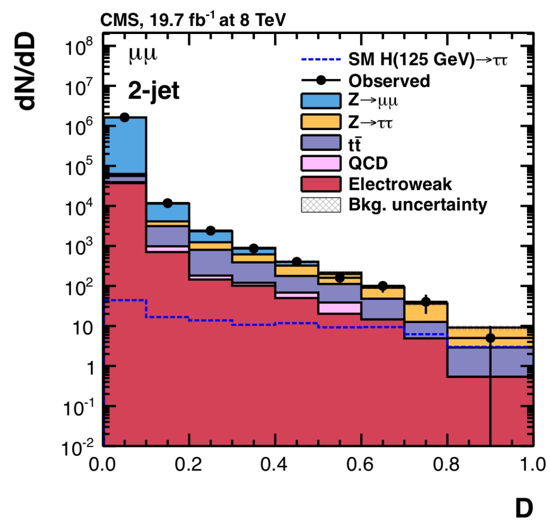
$\tau_h \tau_h$ channel

Comb. BDT Distributions (mm/ee)

ee VBF:

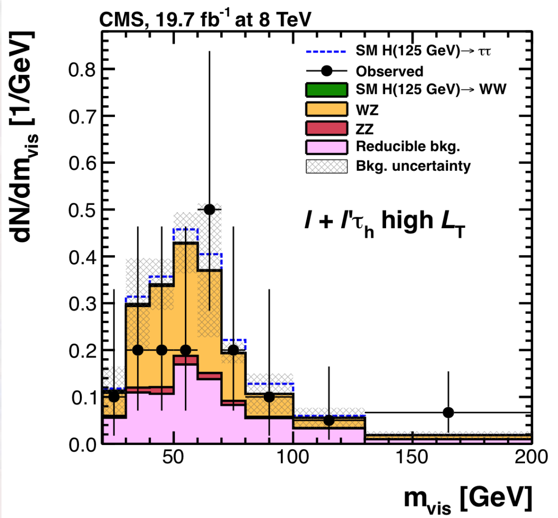


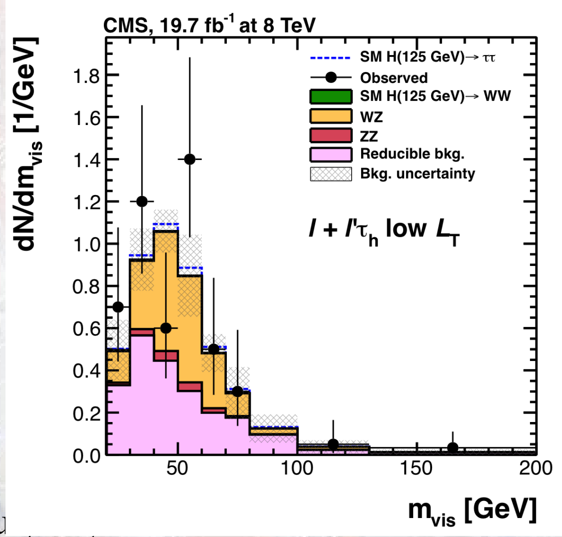
mm VBF:



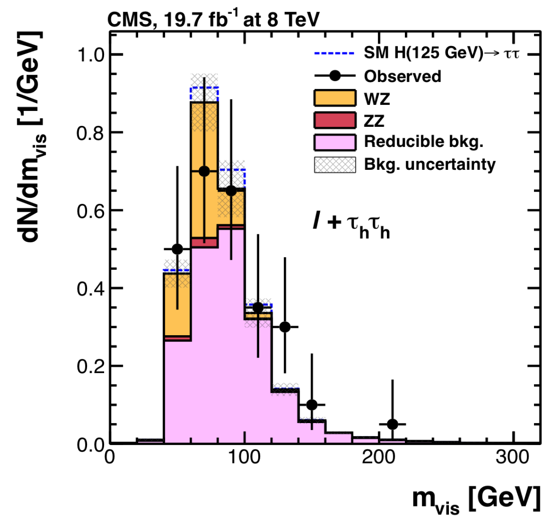
Di-Tau Mass Distributions (VH)

WH semi-leptonic:

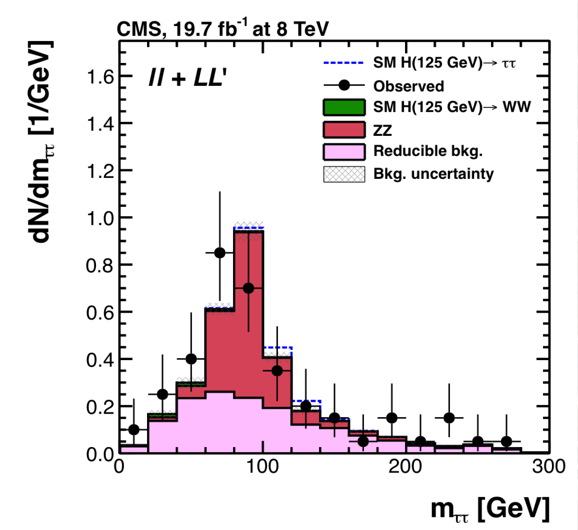




WH hadronic:



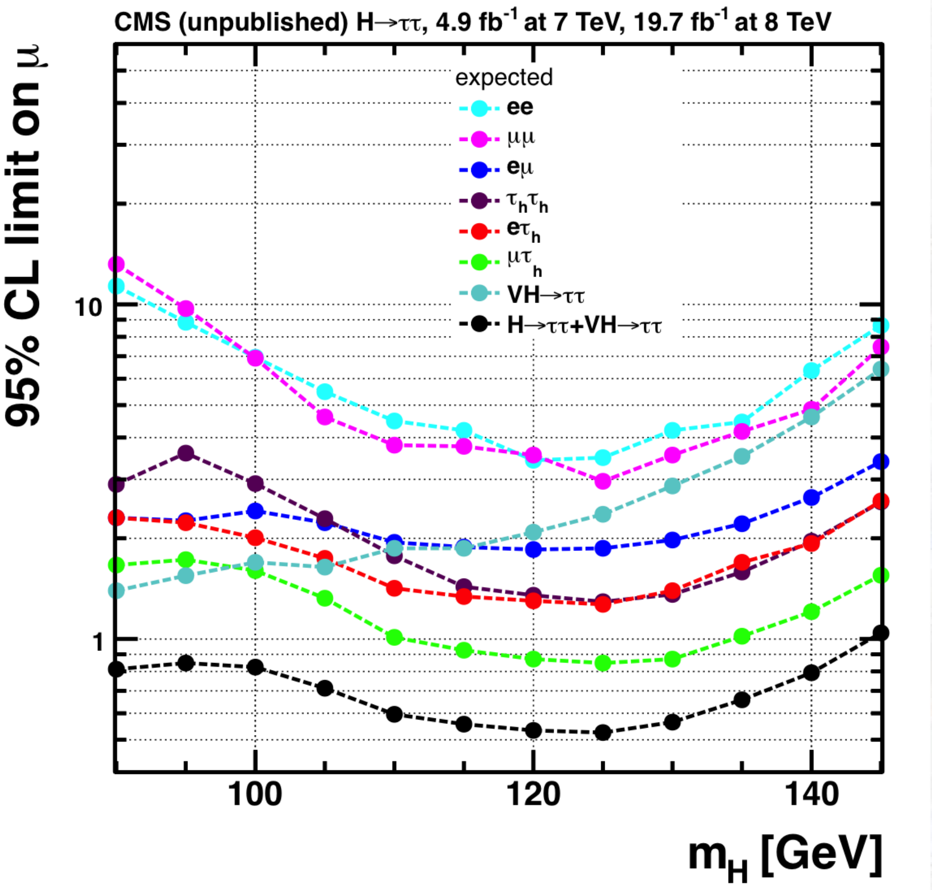
ZH:



VH channels

Expected Limit by Channel

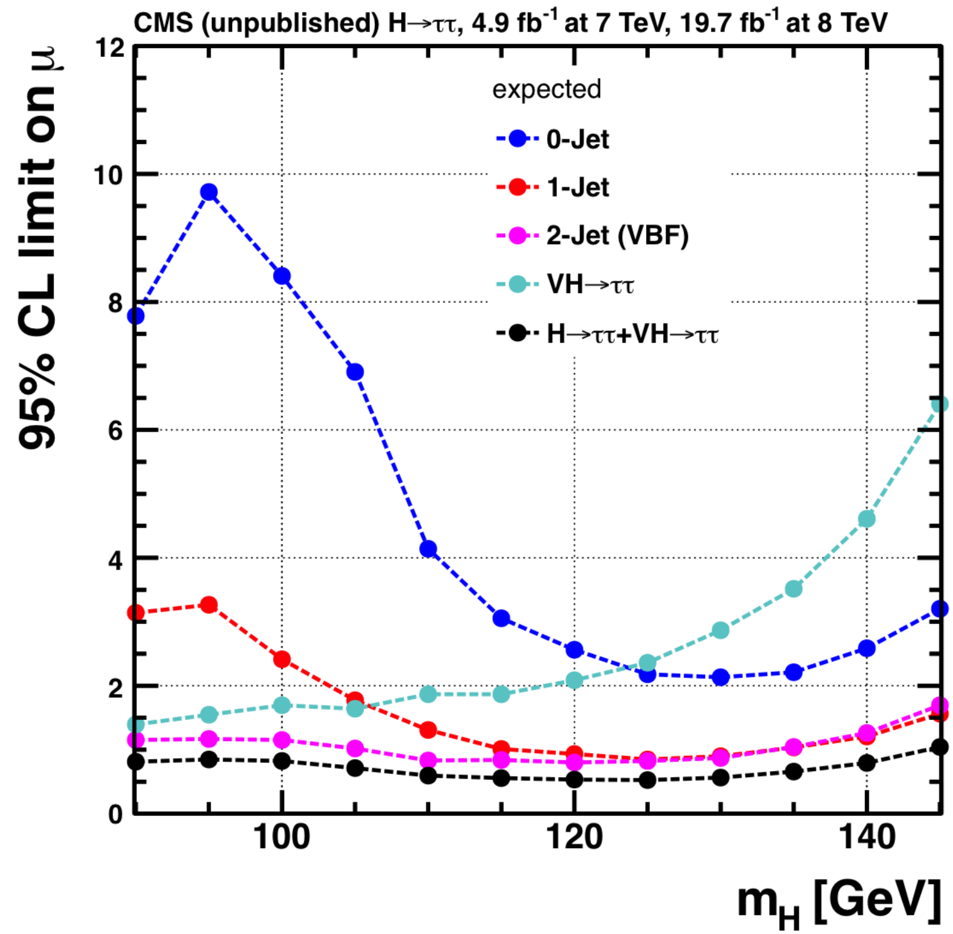
HIG-13-004



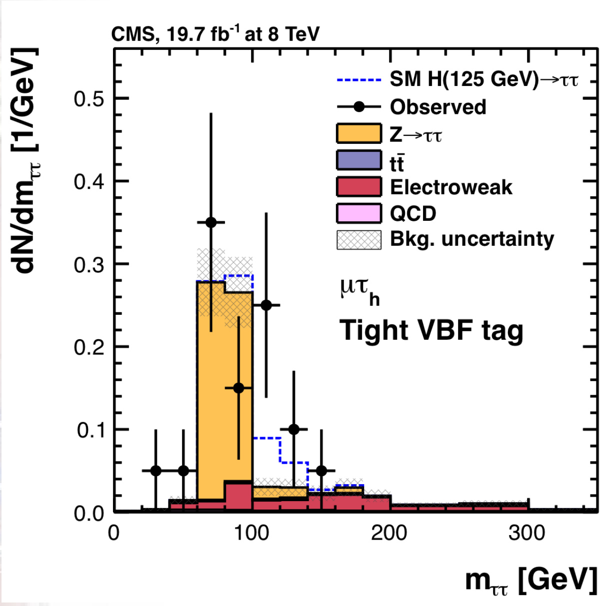
- **Combine all channels** and categories for statistical interpretation
- 95% C.L. Frequentist **Exclusion Limits** are set with the CLs method
- VH channels sensitive at low masses

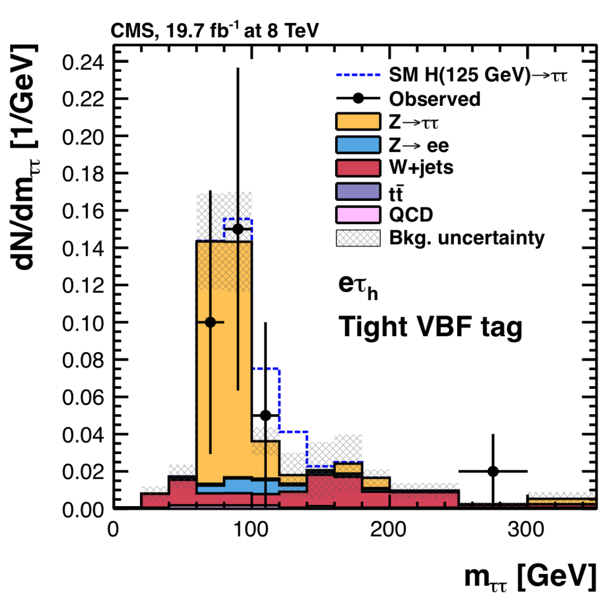
Only combination of channels is sensitive to SM Higgs

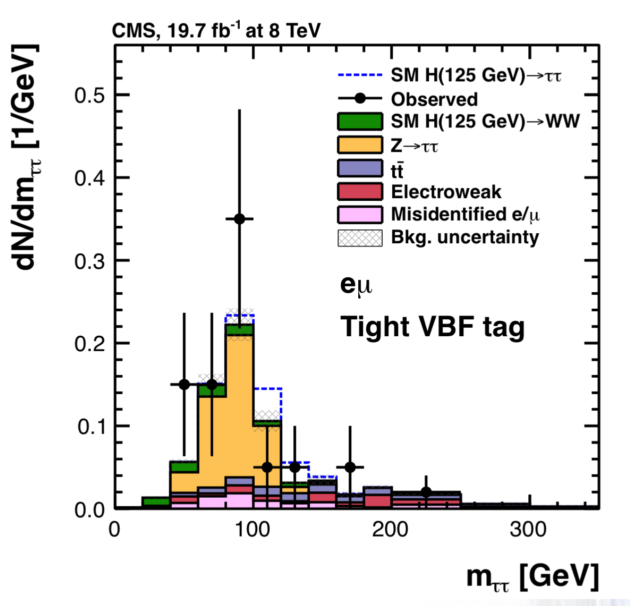
Expected Limit By Category



Tight VBF Category

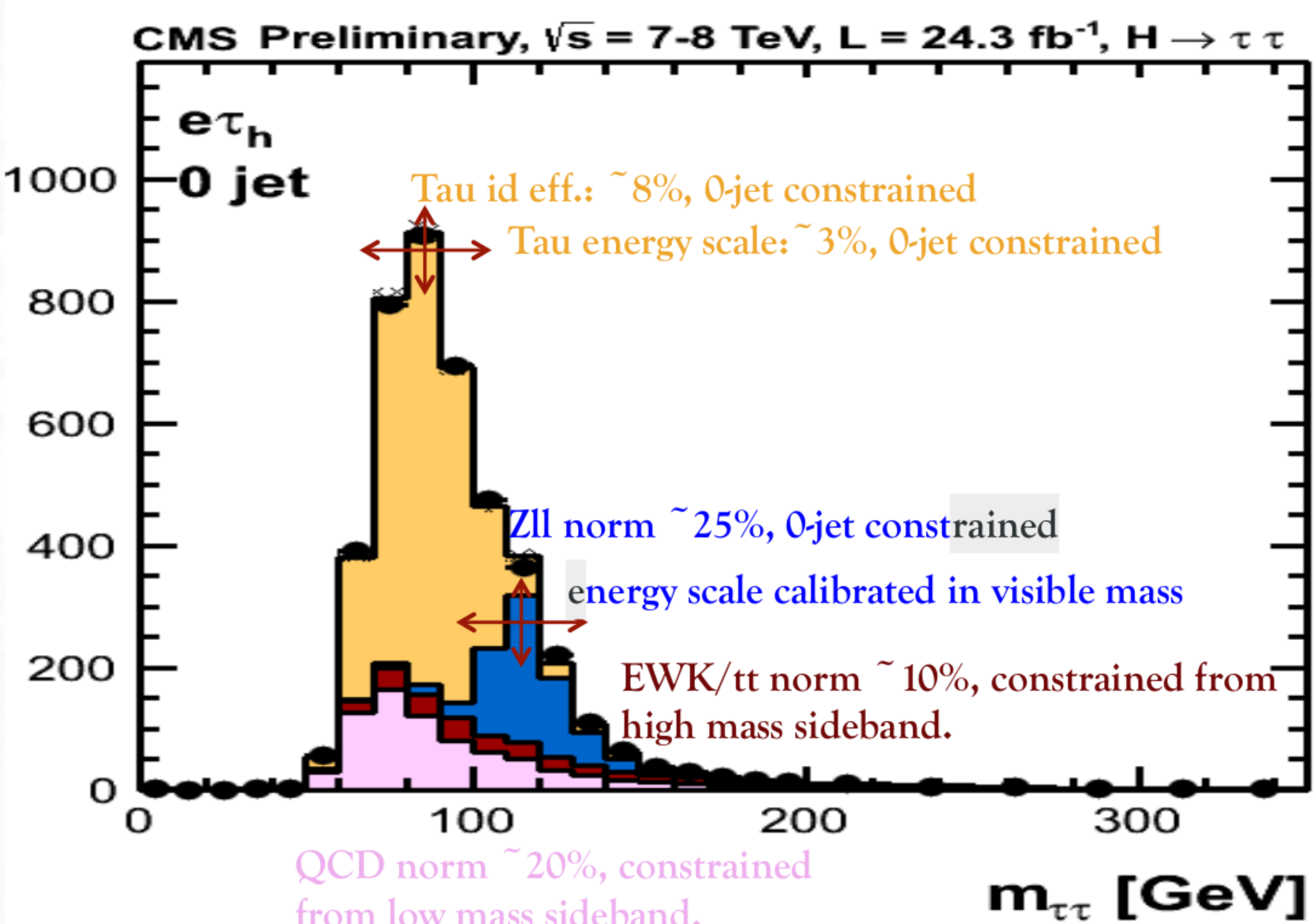






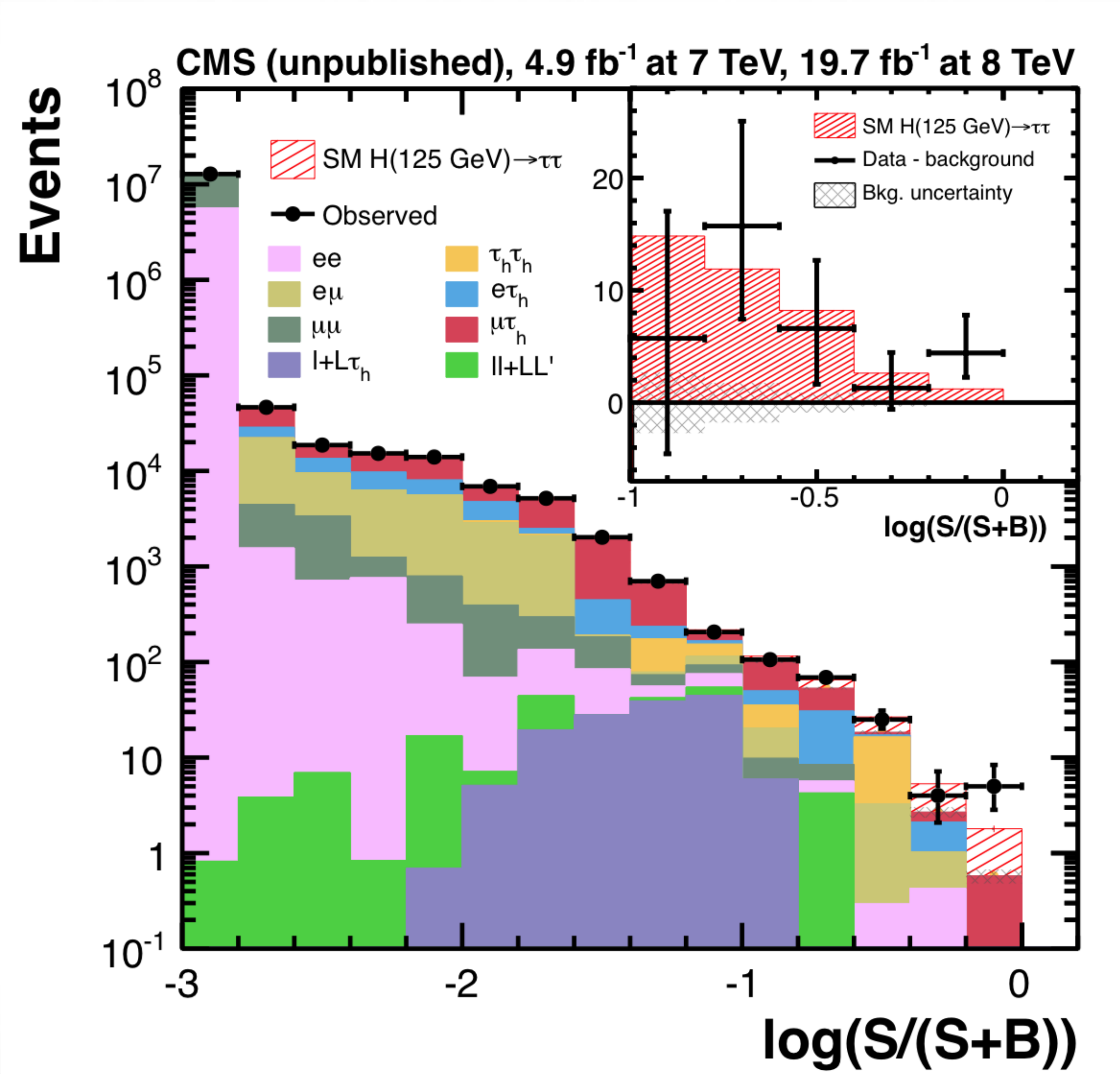
Systematics

on one slide

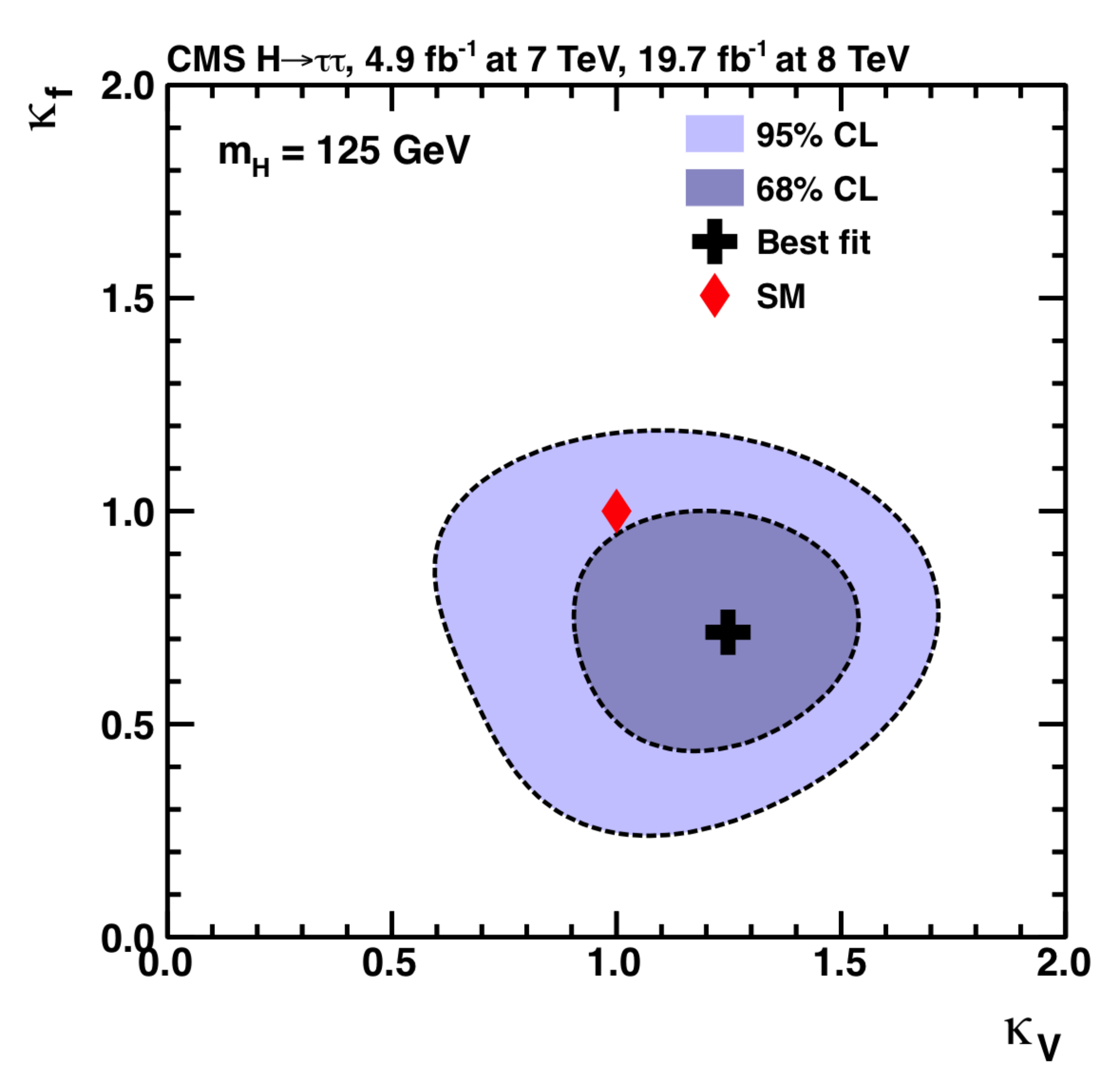


(J. Benitez)

S/(S+B) plot with all analysis bins



cV-cF



H → WW treated as signal

Contraint in κ_V comes from eμ VBF